EVALUATION AND PRELIMINARY RESULTS OF THE NEW USNO PPS TIMING RECEIVER

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Abstract

The U.S. Naval Observatory (USNO) is tasked to provide the Global Positioning System (GPS) with a reliable and stable reference to UTC(USNO). This is accomplished using GPS Precise Positioning Service (PPS) timing receivers with a UTC(USNO) reference input. The USNO monitors GPS Time from all available healthy satellites. On a daily basis, the GPS Time correction, based on the entire constellation with respect to UTC(USNO), is determined and provided to the GPS Master Control Station (MCS) 2nd Satellite Operations Squadron (2 SOPS) at Schriever AFB in Colorado.

The USNO's GPS PPS operations have been limited to a single-channel receiver, which only allows tracking of one satellite at a time. Since February 2000, the USNO has been evaluating a 12-channel GPS PPS timing receiver, based on the GPS Monitor Station receiver. The unit is capable of tracking P(Y)-code and removes the effects of Selective Availability (SA). This paper describes the various tests conducted, the receiver's performance, and expected improvements to the USNO GPS PPS operations.

INTRODUCTION

The Master Clock of the U.S. Naval Observatory (USNO) is the official time reference of the United States as designated by the Joint Chiefs of Staff (JCS) Master Navigation and Timing Plan (MNTP) and the joint Department of Defense/Department of Transportation Federal Radionavigation Plan (FRP). The Department of Defense (DoD), most civilian government agencies, and private industry rely on the USNO Master Clock for their source of precise time. As part of the USNO timekeeping mission, the USNO serves as the precise time reference for the Global Positioning System (GPS).

The USNO measures the GPS time offset relative to the USNO Master Clock located in Washington, D.C. using specialized monitor station GPS timing receivers. These measurements are analyzed and sent daily to the GPS control segment, which then steers the GPS time scale to the DoD Master Clock at the USNO [1]. Over the last 5 years, the GPS time scale has been maintained to within +/-20 nanoseconds of UTC(USNO).

Currently the USNO uses STel 5401C GPS P(Y)-code timing receivers to monitor the GPS time offset. These receivers are based on a single satellite tracking, dual-frequency, P(Y)-code receiver that was developed in the mid 1980s. Because this receiver has only a single tracking channel, a tracking schedule must be used to ensure complete coverage of all GPS satellites. The

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **NOV 2000**	2. REPORT TYPE	3. DATES COVERED **00-00-2000 to 00-00-2000**
4. TITLE AND SUBTITLE **Evaluation and Preliminary Results of the New USNO PPS Timing Receiver**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Naval Observatory,3450 Massachusetts Avenue NW,Washington,DC,20392-5420**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES **See also ADM001509. 32nd Annual Precise Time and Time Interval (PTTI) Meeting, 28-30 Nov 2000, Reston, VA**		
14. ABSTRACT **see report**		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**11**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

internal time-interval counter in these receivers has a resolution of only 9 nanoseconds. Therefore, to improve the precision of the measurements, an external counter with a resolution of 1 nanosecond is used. Also, the receivers are not GPS 1024 week number rollover-compliant. When the GPS week number rollover occurred, the receivers began displaying 6 January 1980 and the date in the receiver data record was incorrect. The USNO overcame this problem by simply correcting the epoch of the data before processing.

Due to the age and technical limitations of the STel 5401C receivers, it was apparent that a new state-of-the-art GPS time monitor receiver would have to be developed. The USNO requirements for the next generation time monitor receiver included P(Y)-code tracking of all GPS satellites in view on both L1 and L2 frequencies under all conditions of Selective Availability (SA), and providing the raw broadcast parameters, as well as code and carrier-phase measurements. In addition to tracking improvements, a modern all-digital design would have to provide sub-nanosecond time-interval measurements for improved long- and short-term stability. The receiver would also require stability to within 1 nanosecond over a temperature range of +/- 5 degrees centigrade.

RECEIVER DEVELOPMENT

In January 1998, Allen Osborne Associates (AOA) was contracted to develop a prototype receiver according to the USNO requirements [2]. Based on the Jet Propulsion Laboratory (JPL) Rogue family of Geodetic receivers, AOA's new BenchMark/TurboRogue geodetic GPS receiver with Advanced Codeless Tracking (ACT) technology and the AOA GPS Monitor Station Receiver Element (MSRE), the TTR-12 Security Module (SM) time monitor receiver was developed. The prototype was delivered to the USNO in August 1999 for test and evaluation. After months of testing, which included returning the receiver to AOA for modifications, it was apparent that the new receiver would be able to fulfill the requirements for a new USNO GPS time monitor receiver. Therefore, the USNO awarded AOA a contract to build four production models, which were delivered by May 2000. However, as of December 2000, the receivers were not in their final state.

The TTR-12 receiver tracks up to 12 GPS satellites simultaneously and provides all six code and carrier observables, whether the P-Code encryption (Anti-Spoofing) is on or off. It outputs carrier-phase and pseudo-range measurements derived from L1-C/A, L1-P(Y), and L2-P(Y) code with full carrier wavelength. The ACT code tracking technology improves upon the P-codeless technique of older generations of Rogue receivers, resulting in an increase of the signal-to-noise-ratio (SNR) on L2 and thus, reduces measurement noise. During normal operation, the TTR-12 receiver will track the true P(Y) code GPS signal. When the receiver is operated unkeyed, the TTR-12 will revert to the ACT code-tracking mode with minimal loss of precision. A commercial time-interval counter with the resolution of 100 picoseconds was integrated into the AOA design to allow the internal measurements to be related to an external clock.

In addition to the improved receiver hardware, USNO has also incorporated into the overall system the Andrews FSJ1-50A phase-stable antenna cable and modified the standard Dorne Margolin choke-ring antenna with temperature-stable electronics built by KW Microwave. The antenna cables and electronics are expected to provide a significant improvement to the temperature stability of the antenna portion of the system.

AOA TTR-12 TEST AND EVALUATION

During the period February 2000 through September 2000, USNO and the Naval Research Laboratory (NRL) conducted a series of tests to evaluate the TTR-12. USNO testing included comparisons with the STel 5401C and other TTR-12 receivers. NRL is the designated DoD agency for GPS timing receiver testing. Their testing was performed using a simulator capable of producing 10 simultaneous signals with SA and A-S. Numerous hardware and software problems were encountered with the testing and a majority were resolved.

SOFTWARE FIXES

When the STel and TTR-12 were compared using horizon-to-horizon tracks, the TTR-12 displayed an unusual trace. The expected trace of a GPS horizon-to-horizon track shows noise at the beginning and end of the track, and reduced noise in the middle. This was not the case for all TTR-12 tracks. After notifying AOA, it was discovered that the orbit iteration process was not being applied for satellites with large eccentricities. Figure 1 shows 5 days of horizon-to-horizon tracks of PRN02/SVN13 from the STel (top trace) and TTR-12 (bottom trace) receivers. Once the software was corrected, the TTR-12 horizon-to-horizon tracks showed an improvement. Figure 2 shows the STel track (top trace), the TTR-12 track before (middle trace) and after (bottom trace) the software fix. The authors would like to note that the AOA TTR-4P receiver continues to be plagued with this problem.

The remaining TTR-12 software fixes include the removal of SA dither at any selected sample output rate and SA epsilons. Live testing of the fixes would not be adequate since SA was set to zero on 2 May 2000, so verification will be done using the NRL simulator.

GPS CARRIER-PHASE TIME TRANSFER

Though software development for the TTR-12 has not yet been completed, in order to provide simultaneous real-time offload of GPS data necessary for the TTR-12 to function as both a GPS MSRE *and* a GPS carrier-phase timing receiver, one may currently obtain raw pseudorange and carrier-phase data by periodically downloading such data from a flashcard. Several preliminary experiments have been performed using data collected from the prototype TTR-12 receivers' flashcards and geodetic GPS carrier-phase techniques to further quantify the quality of the TTR-12.

TEMPERATURE SENSITIVITY OF GPS CARRIER-PHASE CLOCK ESTIMATES

A prototype TTR-12 was placed in a Tenney Environmental chamber oven while purposely varying the temperature in the oven in order to quantify the sensitivity to temperature of the TTR-12 when used for GPS carrier-phase time transfer. The phase-stable Andrews model FSJ1-50A antenna cable connecting the TTR-12 to its Dorne Margolin antenna has been shown to have a temperature coefficient of about 0.03 ps/m/°C [3] while the temperature sensitivity of the Dorne Margolin choke-ring antenna has been inferred to be better than 2 ps/°C [4]. Currently on loan to USNO from the Swiss Federal Office of Metrology is an Ashtech Z-12T (GeTT) GPS receiver (designated USNB). This receiver has the same type of antenna and antenna cable as that used with the TTR-12, but the USNB receiver is housed in a thermally shielded box whose temperature is controlled to within 0.1 °C.

Temperature testing of the TTR-12 was conducted over a 4 day period (22-25 July 2000). The temperature in the Tenney chamber was changed every 6 hours in increments of 2.5 °C over a range of 20 to 38 °C. The 30-second pseudorange and carrier-phase data were used to obtain clock estimates between the TTR-12 and USNB at 5-minute intervals. These estimates were then combined with 1-minute temperature data, ($T_{chamber}$), which were collected from within the Tenney chamber and fit by least-squares to the simple model, (TTR12-USNB) = k ($T_{chamber}$). The resulting fit suggests a temperature coefficient for the TTR-12 receiver of –77 ± 6 ps/ °C. Figure 3 shows the temperature changes to the Tenney chamber and the reaction of the TTR-12 receiver.

POWER CYCLE TESTING

Power cycle testing of the TTR-12 receiver was conducted to verify that the receiver could maintain its calibration and receiver settings such as position and delays. Repeated power cycles indicate that the TTR-12 receiver has the capability to hold its calibration and receiver settings after loss of power.

PERFORMANCE EVALUATION

At the end of September when the USNO was confident that most of the hardware and software deficiencies had been resolved, performance evaluations focused on the GPS Time measurements and hardware stability.

GPS TIME MEASUREMENT STABILITY

Using one week of GPS Time measurements common to the STel and TTR-12, comparisons were made using broadcast clocks and orbits, and then applying the National Imagery and Mapping Agency (NIMA) precise orbit and clock corrections. The STel 13-minute UTC(USNO)-GPS values using broadcast corrections show a 30 to 35 nanoseconds peak-to-peak scatter in Figure 4. When the NIMA precise orbit and clock corrections were applied, the noise was reduced to about 15 nanoseconds peak-to-peak as seen in Figure 5. In Figure 6, the TTR-12 data using broadcast corrections, shows similar results to the STel , as well as an increase of data due to the multiple channels. After applying the NIMA precise corrections to the TTR-12 data, the noise was reduced to about 5 to 10 nanoseconds peak-to-peak, seen in Figure 7.

The Time Deviation (TDEV) plot in Figure 8 shows the STel and TTR-12 stability for UTC(USNO)-GPS using both broadcast and precise orbits and clocks as a function of averaging lengths. The dashed lines represent the STel performance and the solid lines represent the TTR-12 performance. The top two lines near the word "broadcast" represent the time deviation of UTC(USNO)-GPS using the standard broadcast clocks and orbits. The bottom two lines near the word "precise" represent the time deviation of UTC(USNO)-GPS after applying the NIMA precise clock and orbit corrections. In order to make a fair comparison with the STel, the TTR-12 data used are the same tracks used for the STel.

From this data set we can conclude that similar levels of performance of about 4.5 nanoseconds at 13 minutes and 2.5 nanoseconds at 1 hour can be seen in the TTR-12 and STel when measuring UTC(USNO)-GPS using the broadcast clocks and orbits. The noise in the broadcast corrections is larger than both the STel and TTR-12 hardware noise, evidenced by the fact that both the STel and the TTR-12 stability improved when precise corrections were applied. After applying the NIMA precise clock and orbit corrections, we see that the TTR-12 hardware is more stable than

the STel hardware, and that the stability of the TTR-12 UTC(USNO)-GPS measurements approaches 1 nanosecond at 13 minutes, and is sub-nanosecond thereafter.

RECEIVER HARDWARE STABILITY

Figure 9 is a TDEV plot which estimates the hardware stability of the receivers using GPS common-view. The two methods used were short baseline (co-located on the same roof, 2 to 3 meters apart) and common antenna. The dashed line is the time deviation of common-view between two STel receivers on a short baseline. The solid lines are time deviations for the TTR-12 receivers in several different situations. The top line represents the TTR-12 as if it were a single-channel receiver using the same tracks as the STel. The stability at one day for the STel is 400 picoseconds and the TTR-12 is 300 picoseconds. Although the short baseline common-view results are an estimate of the hardware stability, the results could be corrupted by multipath differences at the two antennas, differences in antenna hardware, cable quality and differences in the environment of the antennas and cables.

The Short Baseline Advanced Common-View (ACV) method represents the TTR-12 hardware stability where all common-view tracks for one single timestamp are averaged together. At 13-minutes, the stability drops down to 500 picoseconds and 90 picoseconds at 1 day.

The Common Antenna ACV represents the best estimate of the TTR-12 receiver hardware stability available. From this data set, it can be concluded that the TTR-12 hardware is quieter than the STel hardware over all averaging lengths, showing stabilities at or below 50 picoseconds over all averaging lengths.

REMAINING TESTS

The remaining tests to be completed at NRL with the simulator are the verification of the SA averaging and epsilons, and absolute calibration of the receivers, antenna cables and antenna electronics. Once these tests are completed, USNO will set up parallel operations with the STel receivers prior to going operational with the TTR-12 receivers.

CONCLUSION

For the future, a SAASM version of the TTR-12 receiver will be built, this being a DoD requirement. A phased array antenna is also being evaluated to decrease multipath and increase signal-to-noise strengths. USNO is encouraged with the hardware improvements that will enable the USNO to provide the GPS Control Segment with more stable and reliable timing corrections for the GPS.

ACKNOWLEDGMENTS

The authors would like to thank Art Dorsey, Lockheed Martin Company for his work applying the NIMA Estimated Range Deviations to the USNO data.

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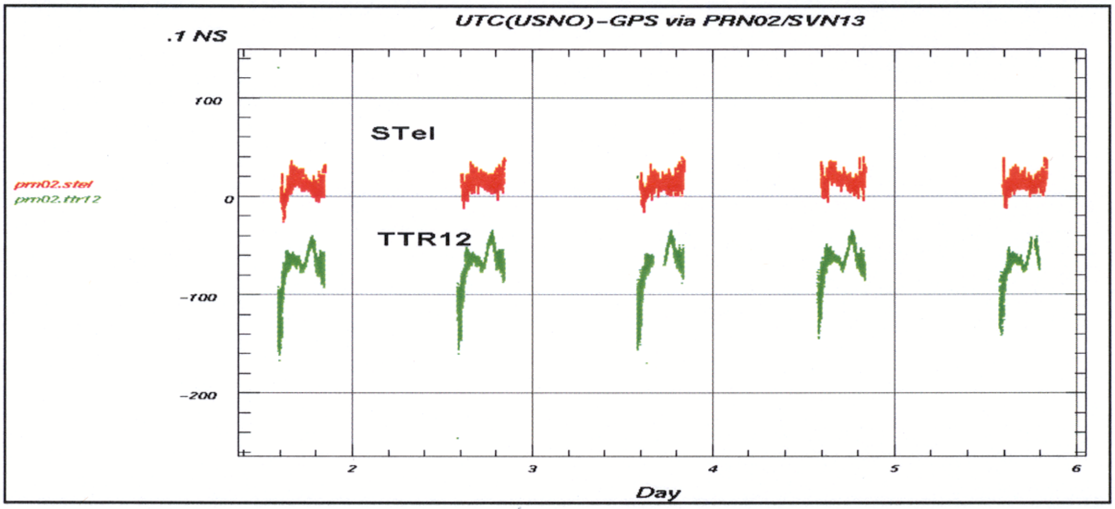

Figure 1. STel and TTR12 horizon-to-horizon tracks of PRN02/SVN13.

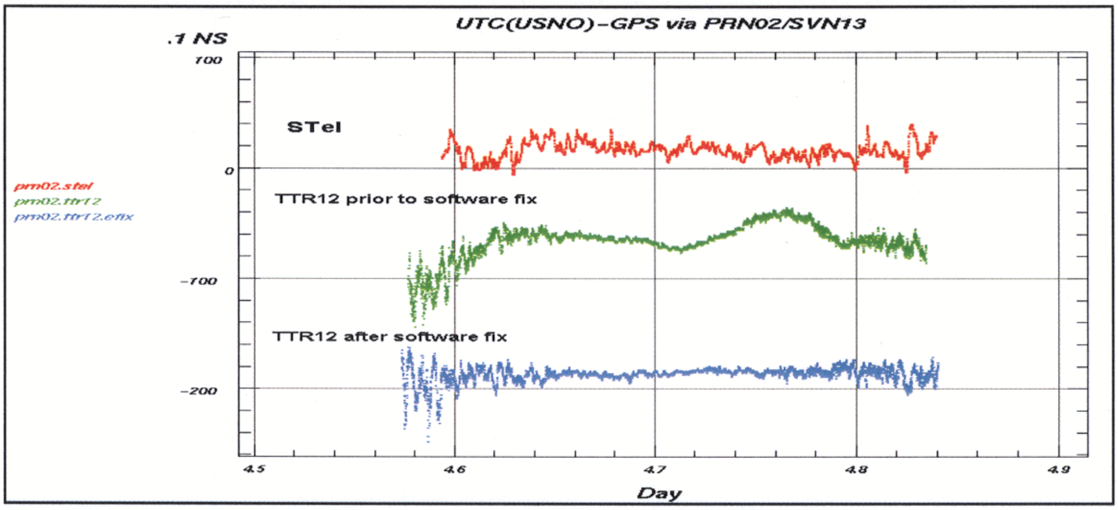

Figure 2. STel and TTR12 horizon-to-horizon tracks of PRN02/SVN13.

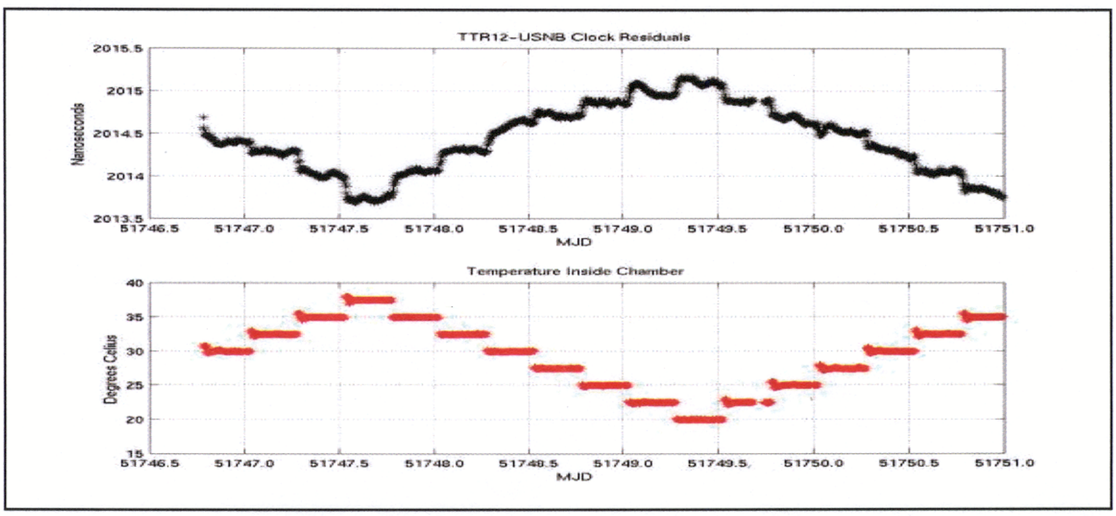

Figure 3. Clock residuals between TTR12 and USNOB, and temperature within Tenney Chamber for the period 22-25 July 2000.

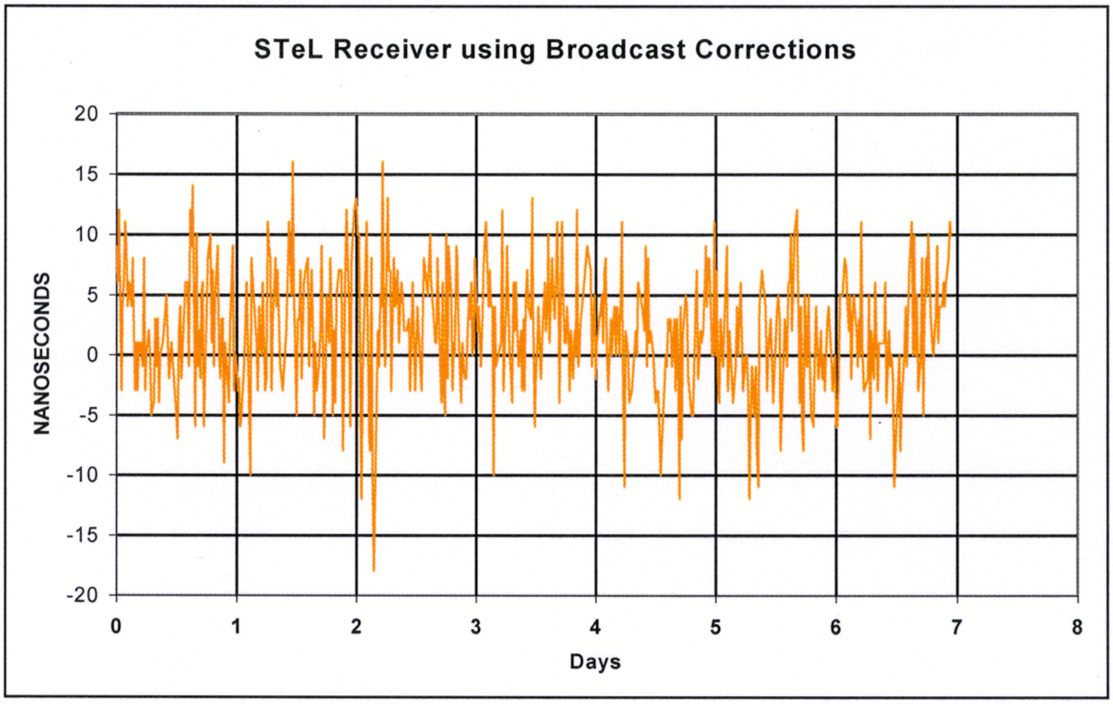

Figure 4. STel 13-minute UTC(USNO)-GPS values using broadcast clocks and orbits.

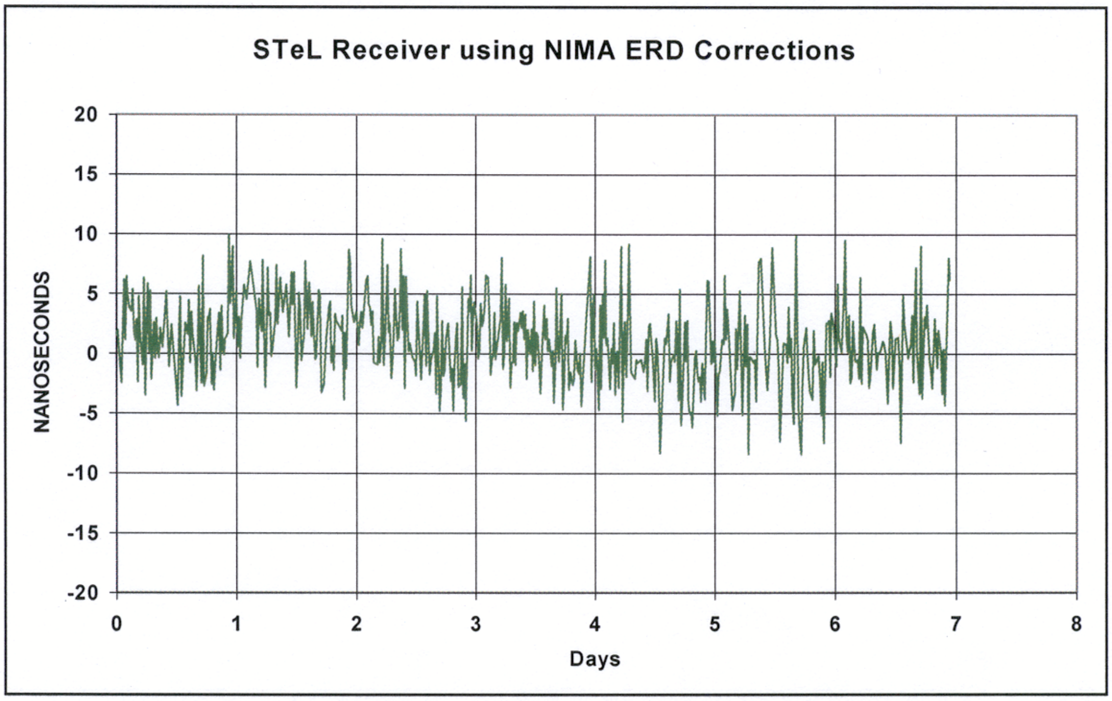

Figure 5. STel 13-minute UTC(USNO)-GPS values using NIMA-corrected clocks and orbits.

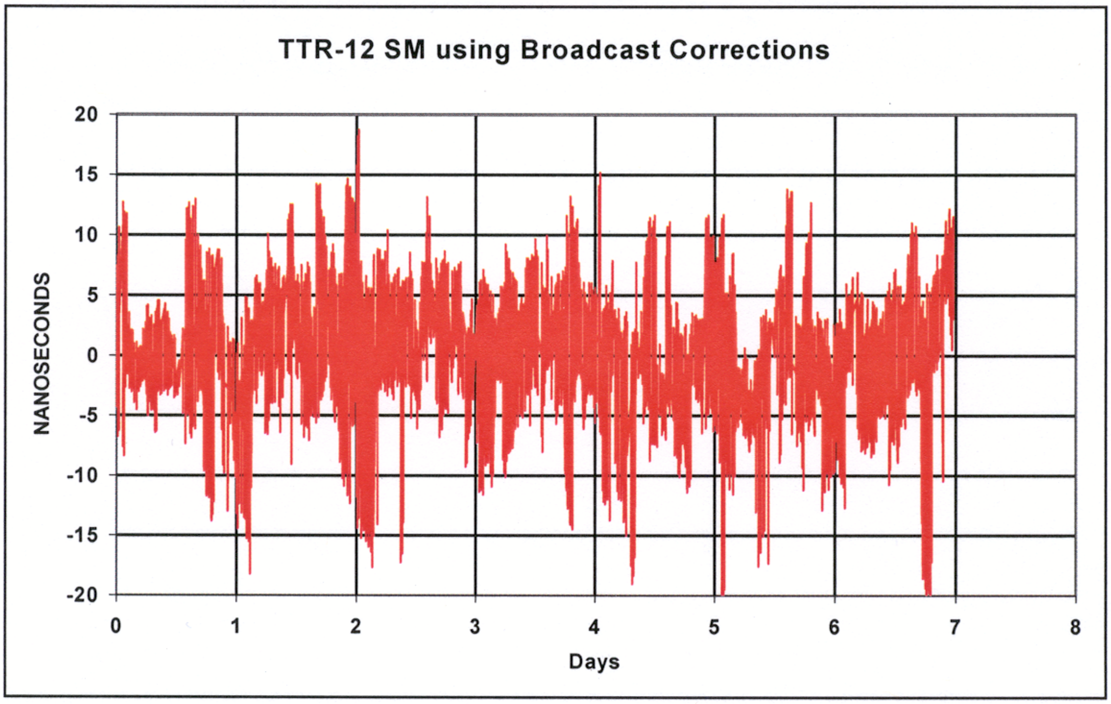

Figure 6. TTR-12 13-minute UTC(USNO)-GPS values using broadcast clocks and orbits.

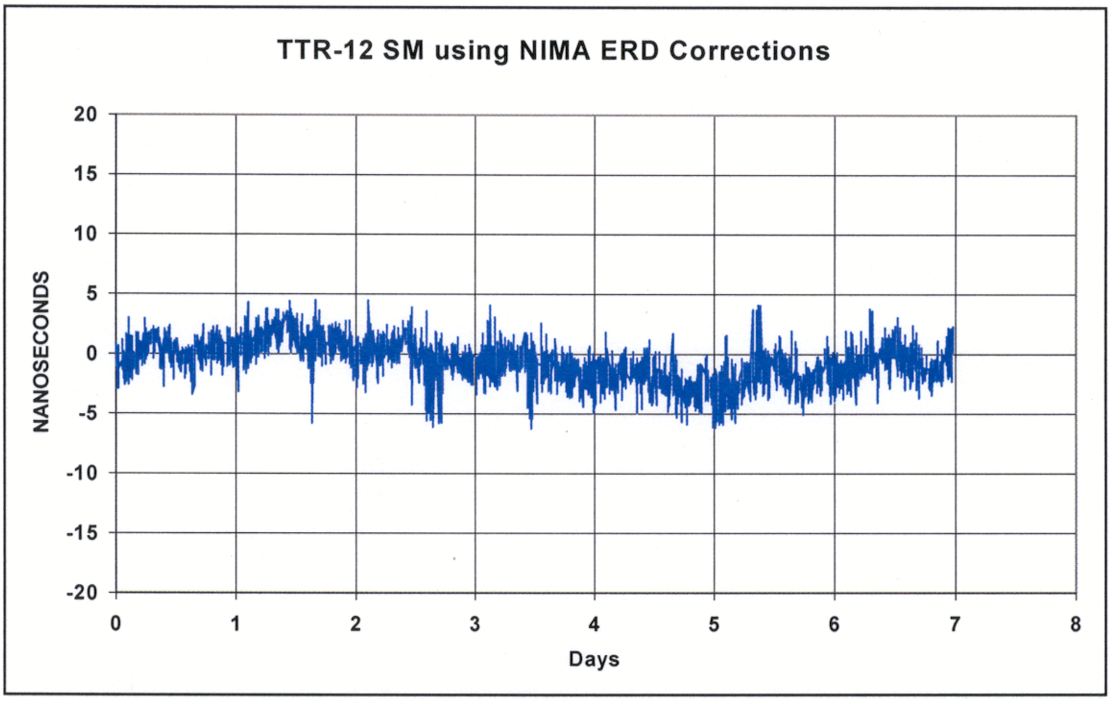

Figure 7. TTR-12 13-minute UTC(USNO)-GPS values using NIMA-corrected clocks and orbits.

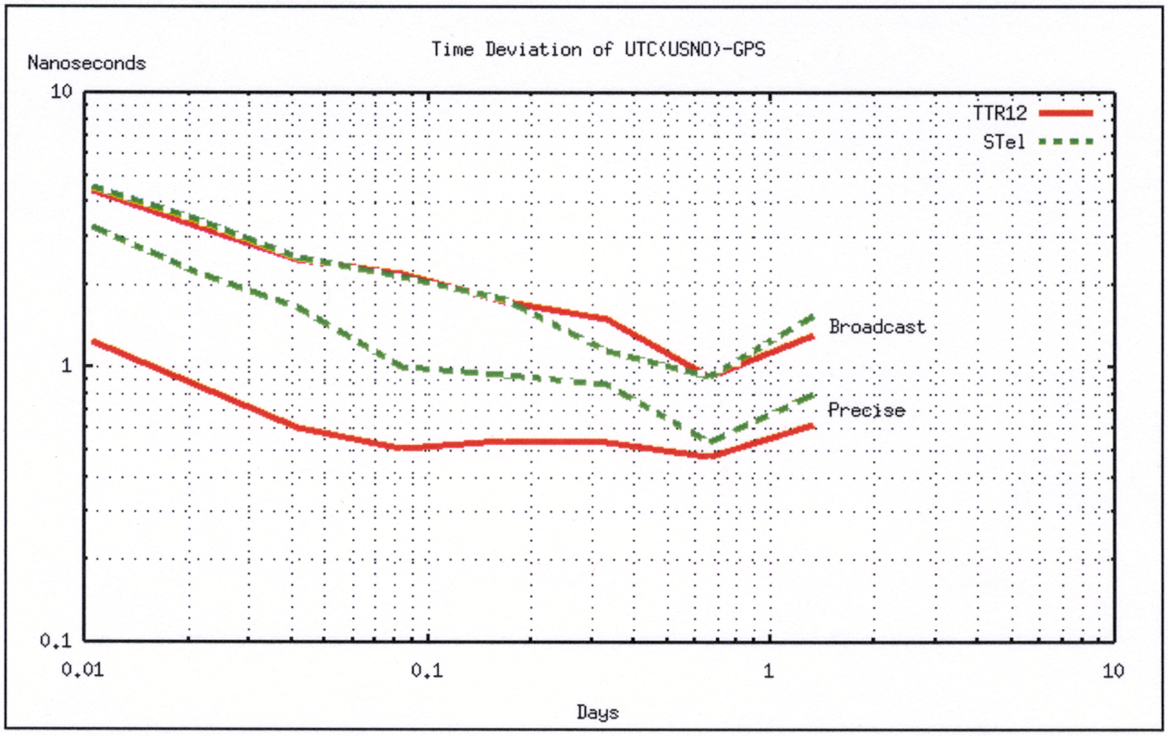

Figure 8. TDEV of UTC(USNO)-GPS for STel and TTR-12 using broadcast and precise orbits and clocks.

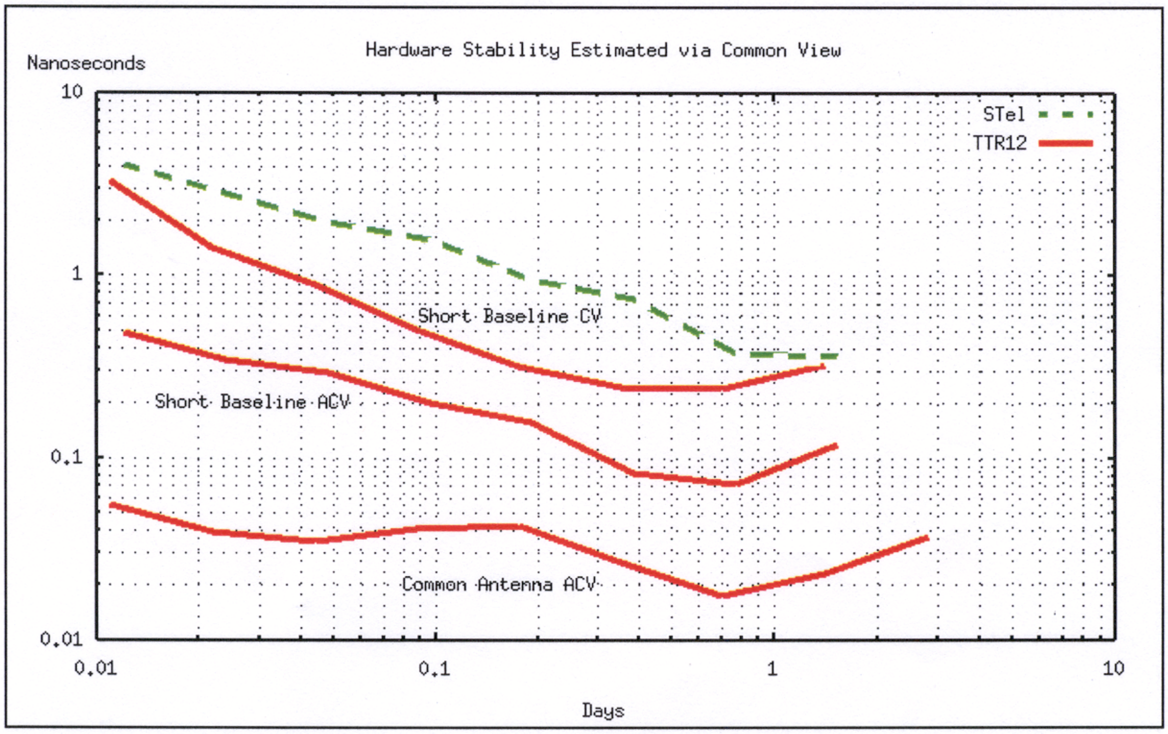

Figure 9. TDEV of STel and TTR-12 hardware stability estimated via common-view.

Questions and Answers

MARC WEISS (NIST): Can you say anything more about that phased array antenna—what are the plans? Is it in design, is it being built?

EDWARD POWERS: We reported last year on work we were doing at the time with NAVSYS to build a dual-frequency P(Y)-code receiver that could eventually be upgraded to the phased array. But since then, we went out and are in the process of awarding a contract. We haven't selected a vendor yet. So we can't talk a lot about that right now. But right now there are two vendors that we're looking at who will build a prototype of this system. It will be a 12-channel dual-frequency 16-element phased array which, the hope is, will get 10 or 12 dB of gain to each GPS satellite, along with maybe a factor of 50 or so reduction in multi-path.

JAMES WRIGHT (Computer Sciences Raytheon): I think in the beginning of your paper you said that there were two contractors that were building a receiver under this study.

FRANCINE VANNICOLA: Right.

WRIGHT: Has the second one materialized and are you testing that?

VANNICOLA: We have not received a prototype to this date, no.

THOMAS CLARK (NASA Goddard Space Flight Center): I'll ask the same question I asked Lisa earlier: How were the L1/L2 biases handled in the results you showed? Was it assumed to be a constant or was it solved for?

POWERS: Yes, right now this is basically handled in the same way as the TurboRogue—something of a calibration bias. For this particular day, the set are actually uncalibrated and mapped in as a clock error. It will be calibrated before we go operational with it. But they are treated right now as being stable with time, as far as the receiver calibration goes.

DAVID HOWE (NIST): Those are fantastic results. To what degree did you take out cable length problems between the antenna and your antenna when you were trying to determine the noise floor using the common antenna mode? Was there any special attention taken?

VANNICOLA: No. We had the antenna cable going into the splitter and then equal lengths going from the splitter to the receiver, so it all cancelled out.

HOWE: Okay, so it was split at the receiver.

VANNICOLA: Yes.